

UCRL- 95242, REV. 1
PREPRINT

CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

THE VALUE OF IN-COUNTRY SEISMIC
MONITORING SYSTEM

W. J. Hannon

This paper was prepared for submittal to
SIPRI/CLIPS Study on a
Comprehensive Test Ban
Ottawa, Canada
October 23-25, 1986

December, 1986

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

The Value of In-Country Seismic Monitoring Systems*

W. J. Hannon

**University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550**

Abstract

In-country seismic systems are elements of most proposals for monitoring a Comprehensive Test Ban (CTB). These systems consist of data acquisition and processing hardware and appropriate operational procedures for site selection, data analysis and reporting. The proximity of the in-country stations to potential evasion sites allows the use of multiple seismic waves at each station to detect and identify evasion attempts. Even with extensive, in-country systems, earthquakes with explosion-like properties and chemical explosions will produce significant numbers of false alarms. In-country seismic systems have also been proposed to prevent clandestine, off-site testing and estimate yields for a Low Yield Threshold Test Ban (LYTTB). Verified constraints on the source environment, extensive, validated calibration procedures, significant on-site inspection and the validation of new techniques are required if the yield estimation properties of such networks are to be of significant value. Evaluation of the acceptability of specific systems is difficult given the broad spectrum of values of the decision makers (e.g., what is a militarily significant evasion), and the uncertainties in the estimates of capability. Decision analysis is a possible approach to addressing this difficulty.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Introduction

An in-country seismic monitoring system is widely recognized as necessary to obtain an acceptable level of verification for a Comprehensive Test Ban (CTB).¹⁻³ However, even with such a system, some violations could go unrecognized. This fact has lead to the consideration of a Low-Yield Threshold Test Ban (LYTTBT) as a possible alternative.⁴⁻⁷ Some of the proposals for an LYTTB have included the use of in-country monitoring as part of the verification measures.

This paper discusses the value of in-country monitoring systems. It begins with a description of the generic elements of such systems. The verification functions to be performed by the systems are described and technical performance measures are discussed for both CTB and LYTTB monitoring. The paper concludes with a discussion of the decisions that must be made to evaluate the acceptability of the system. The results obtained from using decision analysis to determine the value of specific in-country systems for CTB monitoring provide an example of a possible approach to structuring the compliance evaluation process.

In-Country Monitoring as Part of the Verification Process

For the purposes of the present discussion, an in-country seismic monitoring system refers to that part of the verification process in which seismic and geological data are collected from locations within the country to be monitored, the data are analyzed, and the results of the analyses are reported to those assessing all of the technical, military and political information necessary to evaluate compliance and initiate appropriate responses. The deployment and operation of such a system,

involves a number of interrelated functions (see Table 1).⁷ Since each party to a CTB simultaneously monitors and is monitored by the other parties, the table identifies functions to be carried out by the host nation as well as by the monitoring nations. These functions include site selection, start-up and reporting procedures, as well as the more traditional data gathering and analysis efforts associated with monitoring systems. These additional functions are important elements of the system and are worthy of considerably more attention than they have received in the public discussions to date.

The Technology of In-Country Seismic Systems

In-country seismic systems proposed for reciprocal monitoring of a CTB treaty involving the United States and the Soviet Union involve networks of from 5 to 25-30 seismic stations located at sites within each of the countries.^{2,3,8} The proposed distances between adjacent stations range from less than 1000 kilometers^{2,3} to more than 2000 kilometers.⁸ The general areas in which the stations are to be sited would be selected on the basis of the seismicity of the surrounding regions, estimates of the propagation characteristics of the seismic waves, and proximity to other features that could be exploited for evasion (e.g., regions of dry porous material as well as regions in which salt or hard rock exist with properties such that cavities could be constructed and used to decouple the energy of the explosion from the surrounding earth). Within the general areas, specific sites would be selected to maximize the signal-to-noise ratios for seismic waves originating in areas of particular interest.

The instrumentation proposed for such sites ranges from relatively standard seismic stations^{7,8} to state-of-the-art systems involving seismometers with high

frequency response (30+/-15 Hz) deployed in boreholes to reduce surface noise and/or arrays of more conventional seismometers.^{2,3} The sites would cover areas ranging from less than one square kilometer to several tens of square kilometers. The smaller sites would contain instruments installed in a single borehole and the associated equipment on the surface needed to power the station, digitize the data, and transmit the digital data to remote data centers. The larger sites would be needed for small arrays of 15-30 seismometers together with a central facility for collecting and transmitting the data from the individual sensors.

Recent proposals to enhance the monitoring capabilities of the single borehole sites by using high frequencies depend on exploiting potential improvements in signal-to-noise properties and discrimination between some explosions and some earthquakes at these frequencies.^{2,3} The extent of the contribution of such high-frequency methods is currently being examined. They may be particularly useful to counter evasion schemes based on cavity decoupling (i.e., muffling the signal from an explosion by detonating it in a cavity).

The advantages of arrays are obtained by combining the data recorded by the individual sensors in various ways to form composite data streams with improved signal-to-noise characteristics for signals from specified directions. Achieving the improvement requires that the signals be coherent over the dimensions of the array, and that the noise be incoherent, or have a different direction of approach, velocity, or spectral content than the signal. Since arrays offer the promise of being able to identify the speed of the seismic waves and their direction of approach, the location of the source can be estimated and some properties of the source can be estimated by a single array. Finally, processing the array data may partition the signals from two sources that are close together in space and time. This feature is important when attempting to counter the evasion strategies that involve detonating a clandestine

explosion immediately after a nearby earthquake or chemical explosion.

Future networks may contain both types of stations. The mix that will be used will depend on the eventual determination of the relative performance of each type in specific environments and against specific evasion scenarios. Both technologies can be installed at a single site. The use of arrays of high-frequency sensors, as opposed to an array of conventional seismometers colocated with a high-frequency borehole element, is being examined. However, the basic information about signal and noise coherence at high frequencies needed to evaluate such an installation is currently incomplete.

Functions to be Performed by an In-Country Monitoring System

The data acquisition and analysis elements of both external and in-country seismic systems must be capable of carrying out a number of functions if their performance is to be considered acceptable for monitoring a CTBT. The functions include: (1) detecting the seismic waves generated by militarily significant, clandestine nuclear explosions conducted by an intelligent evader; (2) associating the seismic waves recorded at multiple stations and the multiple seismic waves recorded at a single station with a common source located at a specific location; (3) recording and measuring those properties of the signal that can be used to characterize the strength and characteristics (e.g. pattern of energy radiation, frequency content) of the source; (4) using the measured properties to discriminate between clandestine nuclear explosions and other events, e.g., chemical explosions, rockbursts, and earthquakes.

The heterogeneity of the earth, the variability of the natural and man-made sources, and the ingenuity of the potential evader will introduce uncertainty into the monitor's ability to detect, locate and identify any given event. This uncertainty then becomes part of the monitor's compliance evaluation process. Evaluation techniques such as decision analysis are applicable to the process.⁹ Similar uncertainties affect the potential evader's ability to carry out successful evasion. However, the evader's uncertainties are less than those of the monitor. The evader can calibrate the in-country monitoring system and systematically select operating conditions that favor evasion because the host country will know the present and past properties of the data from the in-country stations under a variety of conditions.

Even if an event is detected, the combination of the technical uncertainties and the decision criteria determined by the value judgments of the monitor may not allow the monitor to be highly confident that the event is not a clandestine nuclear explosion. In these cases, the information from the in-country system can be used to target other national technical means (e.g., satellites) and to help select locations for on-site inspections. Evidence from all means will be combined to form a final evaluation of the unidentified source.

Monitoring Advantages of In-Country Stations

Networks of in-country stations offer some significant monitoring advantages because of the proximity of some of the stations to the possible sources. The stations at regional distances from a source (i.e, distances less than 2000 km) record multiple seismic waves which, in general, have larger amplitudes and higher

frequency content than the seismic waves from the same source recorded by stations at teleseismic distances (i.e. distances greater than 2000 km.) (see Figure 1).

The multiplicity of waves results from the variety of paths that energy can follow as it travels in the earth's crust and upper mantle from the source to the monitoring stations. The energy recorded at the station as a particular seismic wave follows a path that left the source at a specific angle. If the individual waves recorded at regional stations can be identified, then, in effect, they provide different windows into the pattern of energy emitted by the source. These different views of the source offer the possibility of improved discrimination among source types. This is a topic of active research.¹⁰

The larger amplitudes and increased frequency content of the regional seismic waves reflect the reduced effect of attenuation and the presence of scattering over the shorter, shallower paths. The effects vary from path to path, and the causes of the variations in the observations are topics of current research. Also, because the noise tends to decrease with increasing frequency in the 1 to 50-Hz range, the signal-to-noise ratio could increase at high frequencies even if the high frequency propagation is less efficient than claimed. The extent of the contribution of high frequency waves to verification will also depend on the variability of the high-frequency content of the sources. This, too, is a topic of current research. However, when combined with external stations, in-country seismic systems will provide improved detection and discrimination in all geologic environments.

In-Country Stations vs Specific CTB Evasion Techniques

In-country stations are valuable for monitoring a CTB because of their ability to counter specific evasion techniques reduce the number of large unidentified events, and deter evasion. Three evasion techniques have been extensively discussed in the literature: (1) simulating earthquake waveforms by detonating multiple explosions appropriately distributed in time and space; (2) hiding the signals from the clandestine explosion in the signals of an earthquake; (3) reducing the signals from the clandestine explosion by detonating it in dry, porous material or in a cavity. In each case teleseismic stations are of limited benefit in detecting and/or identifying the clandestine explosions.^{11,12}

The in-country systems are able to effectively counter the multiple explosion scenario by comparing the pattern of arrival times, relative amplitudes, and frequency content of the multiple regional waves recorded by the network with the patterns expected from earthquakes in the same region. For example, the spatial and temporal distribution of the explosions may be able to mimic the sequence and properties of waves from a shallow earthquake in some directions and at some distances but not others. The sampling of the wave field provided by the in-country network will detect these variations. Furthermore, the broader frequency range recorded by the in-country network provides a means to discriminate between the relatively uniform frequencies generated by the individual explosions representing specific waves and the characteristic frequencies of the waves they are intended to mimic.

These same properties of the network allow the in-country stations to effectively counter the hide-in-earthquake scenario. The differences between the relatively low-frequency content of a large teleseismic earthquake and the higher

frequencies of an explosion even at teleseismic distances allow comparatively straightforward separation of the two signals by filtering the records. Figure 2¹³ illustrates the separation which is possible using signals from an explosion which, by chance, were recorded during the arrival of signals from a distant earthquake. Regional earthquakes and nearby explosions pose a more difficult problem both to the evader and to the monitor. The evader has to wait until an earthquake occurs near the explosion site and then determine the location and ultimate magnitude of the earthquake in a relatively short time. These time and location constraints are significantly reinforced by the proximity of the in-country stations. Including arrays in the network enhances the ability of even a single site to carry out the spatial resolution of two sources. These increased limitations on the separation between the explosion and the earthquake restrict the opportunities to exploit large, but infrequent, earthquakes that could overwhelm the recording at key stations. If the waves from both sources are recorded (that is, the earthquake does not saturate the recording system), then the use of frequencies above even 5-10 Hz will allow separation of the signals from the two sources. Improvements in earthquake prediction, earthquake triggering, or the exploitation of earthquake swarms or aftershock sequences could make this scenario more attractive to the potential evader. However, the evader's logistical problems would still be great, and the in-country stations significantly increase the probability that the evasion will be detected.

In large measure, the in-country network necessary to acceptably monitor a CTBT is determined by the third evasion method, decoupling, in which the explosion is detonated in dry, porous material or in a large cavity, reducing the seismic signals transmitted into the earth. Figure 3 illustrates the reduction in

seismic magnitude that occurs as a result of decoupling. It also shows the detection performance of some representative monitoring networks. The figure shows that a 1-kt, fully decoupled explosion is equivalent to a seismic event with a magnitude near two, and that a similar explosion occurring in dry porous material would have a magnitude in the low threes. Although explosions with yields less than 1 kt have been fired in all three underground coupling environments, the magnitude-yield relationship at these levels are uncertain. Thus, the curves are shown as dashed lines for yields less than a few kt. Estimates of the detection capability of worldwide networks⁸ indicate that explosions with such small magnitudes would, in effect, be invisible. Current analyses^{2,3} estimate that in order to monitor an area the size of the Soviet Union, at least 25-30 high-performance in-country stations are required to detect a 1-kt event decoupled in a cavity. These stations will achieve signal-to-noise characteristics better than those observed at conventional seismic stations by summing signals from multiple sensors and recording in different frequency ranges. Fewer stations could detect 1-kt explosions fired in dry, porous material (see Figure 4).² (Note--such material is not thought to be very widespread in the Soviet Union, but knowledge of Soviet geology is quite limited outside of the Soviet Union.)

The efficiency of the discrimination process at these low levels is a topic of current research.^{14,15} If networks operating near their detection threshold, are able to identify 96% of the earthquakes recorded,¹⁴ then given the estimates of the number of shallow earthquakes in the Soviet Union each year as a function of magnitude¹⁶, the annual number of unidentified earthquakes at each magnitude level is shown in Table 2. Even given such optimistic discrimination performance a network whose detection threshold approaches magnitude two could have as many as 100 or more unidentified earthquakes per year that could not be distinguished from explosions.

In addition, the many chemical explosions greater than 20 tons conducted each year will pose significant discrimination problems. Since at present, they cannot be distinguished from nuclear explosions, they are potential sources of false alarms as well as possible masks for clandestine nuclear explosions. It may be possible to address the compliance issues raised by chemical explosions greater than several hundred tons through inspection measures similar to those described in the unratified treaty governing Peaceful Nuclear Explosions.¹⁷ However, the smaller explosions, whose seismic signals are similar to those from a 1-kt decoupled nuclear explosion, are too numerous to handle by such measures. Therefore, unless very efficient discrimination measures are found for such events, they will be a continuing source of concern as long as cavity decoupling is considered a viable evasion scheme.

In-Country Systems vs LYTTB Evasion

In-country networks may be needed for monitoring a LYTTB (which would allow nuclear explosions with yields less than the threshold at designated sites) if the threshold is low enough. The networks could perform three functions: yield estimation for the explosions at the permitted sites, monitoring for clandestine explosions conducted away from the permitted sites, and acquisition of data which could be used to evaluate and develop monitoring capabilities for lower thresholds or a CTB. In the first function, the characterization of the size of the source provides the required monitoring function. In the second function, the monitoring functions are qualitatively similar to those proposed for a CTBT. However, the monitoring requirements may be relaxed somewhat because evasion will almost certainly involve yields greater than those that can be detonated at the designated test sites. The third function

establishes confidence that further reductions can be acceptably monitored. This requires that the monitoring measures installed at any given level be more stringent than the monitoring requirements necessary for that level.

Figure 3 shows that explosions with yields of about 5-10 kt detonated in hard rock and well-coupled to their surroundings will be detected with good signal-to-noise ratios by external networks. Assuming that validated magnitude-yield relationships have been determined for the site to be monitored through the use of calibration events, such external networks should be able to estimate the yields of such events with accuracies similar to but less than those achievable at higher yields. In-country stations could improve the accuracy of the yield estimates by providing an independent yield estimate which could be combined with teleseismic estimates to improve accuracy.

However, 5-10 kt explosions can also be detonated in dry, porous material or partially decoupled in cavities. If suitable on-site inspection measures were instituted, these situations could be identified so that the possibility of systematic errors could be reduced. Even if such situations were recognized, the signal-to-noise ratio for these partially decoupled events would be lowered and the accuracy of the yield estimates made by external stations would be significantly degraded. In addition, the uncertainty would increase because of the increased variability in coupling that is possible in such media and because of the effects of variation in depth of burial and proximity to the water table on the waveforms currently used to estimate yields.

A network of in-country stations surrounding the test site would improve the accuracy of the yield estimates of partially decoupled events in the 5-10 kiloton range. Regional seismic waves such as Lg which propagate in the crust of the Earth¹⁸ (see Figure 1) are the bases for the improvement. Such methods are still

being researched and appear to depend somewhat on the properties of the source and receiver. The network would have to be calibrated by a series of explosions whose yields and source regions were validated. New explosions would be required to be detonated near the calibration events and on-site inspections would be necessary to insure that the materials in the source region were similar for the calibration events and the new events whose yields are to be estimated. Even with such measures, the same increased uncertainties due to variations in depth of burial and material heterogeneity would exist.

For thresholds less than a few kilotons, systematic uncertainties in both the teleseismic and the in-country measurements could result from these same factors. Given these uncertainties, distinguishing between explosions at the threshold and explosions 3-4 times larger with high confidence and a low false alarm rate could be difficult. Thus, without strictly limiting the explosions to well-characterized, constrained environments, even in-country stations may not provide sufficiently accurate yield estimates for LYTTBs with thresholds less than a few kilotons. However, in-country stations deployed for yield estimation under such a LYTTB would gain experience for off-site monitoring in the vicinity of the test site that would be of limited value under a CTBT.

In-country stations can play an important role in detecting and identifying clandestine explosions conducted at locations other than the test sites permitted under a LYTTBT. Partial decoupling of explosions with yields less than 10 kt could produce signals which would not be identified by an international external network.⁸

Thus some in-country stations would be required to identify such explosions. For a 1-kt threshold, the in-country network required to prevent significant off-site testing would be nearly equivalent to that necessary to monitor a CTB.

The above discussion has not addressed the monitoring issues raised by permitting peaceful nuclear explosions in conjunction with a LYTTB. Almost every aspect of yield estimation is more difficult for such explosions because of a lack of calibration. It may be possible to employ yield estimation techniques using the speed of shock waves measured near the source,¹⁹ but the accuracy of such techniques at low yields is uncertain. Such measures should be introduced at yields less than the threshold of the associated LYTTB. In-country systems could play a useful role in monitoring such explosions by providing a rough yield estimate. When combined with the deployment of a local seismic network as in the protocol of the current, unratified PNE treaty,¹⁷ they could also help to limit the opportunities for conducting simultaneous clandestine weapons tests at nearby locations.

What is Acceptable Verification?

To discuss the value of in-country seismic systems to the overall verification effort, we must consider the qualities required for acceptable verification. (I have chosen to use the adjective "acceptable" rather than the more common qualifiers "adequate" and "effective"²⁰ to emphasize the role that value judgments play in an evaluation process whose fundamental measurements are subject to uncertainty.) Three qualities have been mentioned, either explicitly or implicitly, for evaluating verification:^{21,22} (1) militarily significant violations must be recognized in time to mount an appropriate response; (2) the false alarm rate must be low

enough to maintain the monitor's confidence and not degrade the potential evader's incentive to comply; (3) the system's capability, when combined with the evader's perceptions of the costs of being caught vs the benefits of successful clandestine testing, should deter evasion attempts.

Translating these elements into operational measures of success requires a combination of military, technical and political judgments. From a practical viewpoint, one of the most important of these judgments in many current discussions is the definition of a militarily significant violation. Forming this judgment involves estimating the immediate and long-term impacts of a test ban and of the potential asymmetry introduced by evasion on such diverse but interrelated elements as stockpile reliability, preservation of infrastructure, ability to respond to developments in the nonnuclear capabilities of the weapons systems, survivability and safety. These impacts must be identified by the military community and evaluated by the decision makers in the broader context of both relative and absolute national security.

In order to evaluate deterrence, the value system of the potential evader must be estimated. The evader presumably attaches some cost to an unsuccessful attempt at evasion and some value to a successful one. These, and related values (e.g, the value attached to acknowledged compliance and the value attached to compliance in the presence of false alarms), may vary with time. Given such estimates of value and assessments of the efficiency of the monitoring systems, expected costs and benefits can be determined and deterrence can be estimated. Informal evaluations of this type have been invoked to argue, for example, that a 30 per cent probability of being caught is sufficient to deter evasion attempts.⁷ Such judgments have significant impacts on the acceptability of a given in-country monitoring system.

Many other factors affect the acceptability of an in-country monitoring system. Intrusiveness, cost and negotiability are also factors that have to be considered from both the monitor's and the potential evader's viewpoints. The whole evaluation must take place in the context of the decision makers' views of national security and the threat posed by the nation to be monitored.

Techniques such as decision analysis allow a structured approach to decision making in complex situations which involve both uncertainties in the technical measures and a variety of value judgments. We have been applying this approach to CTBT verification,^{8,23,24} and have obtained preliminary results for a number of cases. For example, Figure 5 compares the relative value of using external monitoring, a network of 10 relatively standard in-country stations and a network of 30 high-performance in-country installations for cases in which cavity decoupling is a viable evasion method and cases in which it is not. The difference in the relative values of the network of high-performance stations vis a vis the network of simple stations between the two cases is the result of a choice of values that penalizes the high-performance stations for unnecessarily detecting small events (many of which remain unidentified) if cavity decoupling is not a viable option. This figure represents the results of a number of estimates of technical performance and of value judgments. The decision analysis framework treats these as input values that can be chosen by the decision maker. As such, the framework allows parameter studies that identify critical elements in the decision process, and allows the structured comparison of the implications of different value systems. We are beginning a similar structured analysis of the issues associated with LYTTBs.

Conclusions

In-country seismic monitoring systems are composed of data acquisition and data processing hardware as well as procedures to select sites, calibrate the performance of the system in a new environment, operate the system, and report the results in a form useful to the decision makers.

The value of these systems for monitoring a CTB is derived from their ability to counter evasion scenarios such as using multiple explosions to mimic the signals from an earthquake, hiding the signals from a clandestine explosion in the signals from an earthquake, and reducing the signals from an explosion by detonating it in dry, porous media or in a cavity. The decoupling evasion methods pose the greatest challenge, forcing the monitoring system to detect and identify events down to magnitudes of near two. The presence of high-performance in-country stations (small arrays and/or single high-frequency sensors) allows the recording of multiple seismic waves with relatively large amplitudes and high frequencies. In addition, the distribution of the in-country stations allows the wavefield to be sampled at a variety of distances and directions. The interlocking information provided by these observations allows multiple assessments of the source properties. These multiple assessments provide the basis for identifying differences between the evasion attempts and other seismic sources.

Even with networks consisting of 25-30 such high-performance stations, some events whose signals are equivalent to a 1-kt nuclear explosion detonated in a cavity will not be detected. Evasion attempts that are detected may not be identified against a background of thousands of small earthquakes. Unidentified earthquakes, of which there could be a hundred or more, will give rise to false alarms. Chemical explosions will pose severe discrimination problems.

Monitoring a LYTTB requires that the yields of explosions at permitted test sites be estimated with high accuracy, and that clandestine explosions executed away from these sites be detected and identified. Fulfilling this latter requirement for thresholds less than a few kilotons is made difficult by the background of earthquakes and chemical explosions in which the signals from the clandestine event would reside. For LYTTBs with thresholds near 1 kt, the off-site monitoring requirements would be similar to those needed to monitor a CTB.

Yield estimates from calibrated in-country stations, when combined with calibrated teleseismic yield estimates, should improved accuracy for yield estimates in the 5-10 kt range. However, systematic variations in the seismic signals can be introduced by by variations in depth and emplacement material. The accuracy of the combined estimates will decrease for LYTTBs with thresholds less than 5-10 kt without extensive calibration, limitations on the testing environments supported by on-site inspections, and the validation of new techniques using regional seismic waves such as Lg.

The presence of uncertainty in the monitoring capability raises the question of what constitutes acceptable verification. Ultimately this is a value judgment encompassing a wide range of factors, including the military significance of successful evasion, the impact of false alarms, the potential evader's value system and many other factors covering a wide range of military, political and economic issues. The technical results--with their attendant uncertainties--and the value systems of the decision makers--with their differing priorities--can be combined using techniques such as decision analysis. The structuring produced by the use of such techniques allows the identification of important elements in the compliance evaluation process and the evaluation of the effects of differing or changing viewpoints. Such techniques have been applied to analyze the value of in-country systems to CTB monitoring.

References

1. Report of the Geneva Conference of Experts (July 1 - August 21, 1958) in Geneva Conference of the Discontinuance of Nuclear Weapons Tests, History and Analysis of Negotiations, U.S. Department of State Publication 7258, Disarmament Series 4, 1961, pp. 15-18.
2. Hannon, W. J., 'Seismic verification of a comprehensive test ban', Science, vol. 227, Jan. 1985, pp. 251-257.
3. Evernden, J. F., Archambeau, C. B. and Cranswick, E., 'An evaluation of seismic decoupling and underground nuclear test monitoring using high-frequency seismic data', Reviews of Geophysics, vol. 24 no. 2, May 1986, pp. 143-215.
4. Kidder, R. E., 'Militarily significant nuclear explosive yields', F.A.S. Public Interest Report, Journal of the Federation of American Scientists, vol. 38, no. 7, Sept. 1985, pp. 1-3.
5. Brown, H., Thinking About National Security (Westview Press, Boulder, Colorado, 1983), p. 191.
6. Scowcroft, B., Deutch, J. M., and Woolsey, J. R., 'Nukes: Continue the Tests', Washington Post, June 29, 1986, p. C7.

7. Sykes, L. and Evernden, J., 'The verification of a comprehensive nuclear test ban', Scientific American, vol. 247, no. 4, Oct. 1982, pp. 47-55.
8. Conference of the Committee on Disarmament, 'Report to the Conference of the Committee on Disarmament of the ad hoc group of scientific experts to consider international co-operative measures to detect and to identify seismic events', CCD/558, March 1958, Appendix II.
9. Younker, L., Hannon, J., Springer, D., Al-Ayat, R., Judd, B., Morris, P. and Sandling, J., 'Evaluation framework for comprehensive test ban treaty seismic verification systems', Lawrence Livermore National Laboratory, Livermore, California, Rept UCID-20423, April 1985.
10. McLaughlin, K. L., 'Evaluation of small events using the Pearce focal plane algorithm', Teledyne Geotech Alexandria Laboratories, Alexandria, Virginia, Rept. No. TGAL 85-11a, Nov. 1985, pp. 1-7.
11. Evernden, J. F., 'Study of seismological evasion. Part I. General discussion of various evasion schemes', Bull. Seism. Soc. Amer., vol. 66, no. 1, Feb. 1976, pp. 245-280.
12. Evernden, J. F., 'Study of seismological evasion. Part II. Evaluation of evasion possibilities using normal microseismic noise', Bull. Seism. Soc. Amer., vol. 66, no. 1, Feb. 1976, pp. 281-324.

13. Ringdal, F., 'Teleseismic detection at high frequencies using NORSAR data',
NORSAR Royal Norwegian Council for Scientific and Industrial Research,
Kjeller, Norway, Scientific Rept. 1/84-85, Nov. 1984, pp. 54-62.

14. Taylor, S. R., Denny, M. D., and Vergino, E. S., 'Regional $M_b:M_s$ discrimination of
NTS explosions and Western United States earthquakes: A progress report',
Lawrence Livermore National Laboratory, Livermore, California, Rept.
UCID-20642, Jan. 1986.

15. Pomeroy, P. W., Best, W. J. and McEvilly, T. V., 'Test ban verification with
regional data--a review', Bull. Seism. Soc. Amer., vol. 72, no. 6B, Dec. 1982,
pp. 589-5130.

16. Gorbunova, I. V., 'Strong Earthquakes on USSR territory', in Earthquakes in the
USSR in 1973, eds. I. V. Gorbunova, N. V. Kondorskaya, and N. V. Shebalin
(Nauka Publishers, Moscow, 1983), pp. 4-17.

17. United States Arms Control and Disarmament Agency 'PNE treaty', in Arms
Control and Disarmament Agreements, 1982 edition (U.S. Government Printing
Office, Washington, D.C., 1982), pp. 170-189.

18. Nuttli, O., 'Yield estimates of Nevada Test Site explosions obtained from
seismic L_g ', J. Geoph. Res., vol. 91, no. B2, Feb. 1986, pp. 3127-2152.

19. Heusinkveld, M., 'Analysis of shock wave arrival time from underground explosions,' J. Geoph. Res., vol. 87, no. B3, March 1982, pp. 1891-1898.
20. Scribner, R. A., Ralston, T. J., and Metz, W. D., The Verification Challenge (Birkhauser Publishing, Boston, 1985), pg. 19.
21. Martin, J. J., 'Remarks on a review of current progress and problems in seismic verification', in Progress and Problems in Seismic Verification Research, Defense Advanced Research Projects Agency, Arlington, Virginia, Rept. TIO 73-3, 1973, p. 24.
22. Brown, H., 'Statement by Secretary of Defense Brown to the Senate Committee on Foreign Relations: Verification of the Salt II Treaty, July 18, 1979', in Documents on Disarmament, 1979 (United States Arms Control and Disarmament Agency, Publication III, Washington, D.C., 1982), pp. 439-488.
23. Strait, R. S. and Sicherman, A., 'Comprehensive Test Ban Treaty seismic verification decision analysis computer model, vol. I & II', Rept. UCID-20704, Lawrence Livermore National Laboratory, Livermore, California, Mar. 1986.
24. Judd, B. R. and Younker, L. W., 'Decision analysis: Evaluating verification options', in Energy and Technology Review, Lawrence Livermore National Laboratory, Livermore, California Rept. UCRL-5200-86-8, Aug. 1986.

**Table 1. Functions necessary to deploy and operate
an in-country seismic monitoring system.**

1. Determine the properties of an acceptable system:

2. Negotiate:

Prepare proposal

Analyze counter-proposals

Develop responses

3. Exchange and assess pre-installation data:

Prepare geological data package to be handed over

Analyze geological data package received

Revise

Iterate

4. Deploy equipment:

By the country doing the monitoring

Obtain information about sites

Select sites

Select instrumentation for each site

Install and check out equipment

By the country being monitored

Determine acceptability of sites

Monitor installation

Participate in check out

Table 1. (Cont'd.)

5. Carry out monitoring functions both as monitor and as one being monitored:

Carry out start-up procedures, e.g., calibrate network,
characterize site and path

Compare actual conditions with estimates

Seek changes if mismatch

Operate and maintain equipment

Archive equipment status and seismic data

Process data

Characterize properties of the signals/sources

6. Coordinate with other technical elements:

National technical means

7. Report results to decision makers:

Events detected

Locations

Estimate of source type

Uncertainties

Rank unidentified events

8. Attempt to resolve ambiguous events in both countries:

On-site inspections

Table 2. Approximate number of unidentified events per year from
high-performance seismic systems monitoring
the Soviet Union.

Detection threshold	No. of earthquakes in Soviet Union per year	Approx. No. of unidentified earthquakes per year ^a
m_b	$\geq m_b$	$\geq m_b$
4.0	100-300	0-10
3.5	270-800	10-30
3.0	700-2000	20-60
2.5	1800-5300	60-200
2.0	4600-14000	100-400

^a Assumes 4 per cent of the earthquakes within 0.5 magnitude units of the detection threshold will not be identified.

Figure Captions

1. Panel (a). Regional seismic waves (recorded at distances less than 2000 km) follow a variety of paths in the crust and mantle of the earth. They exhibit larger amplitudes and higher frequencies than teleseismic waves. Panel (b). A regional seismic record from a well-coupled nuclear explosion at the Nevada Test Site measured at Elko, Nevada (distance: 400 km). The multiple bursts of energy are each associated with a distinct path. In general, the earlier arrivals are associated with the deeper paths in the heterogeneous crust and upper mantle. Panel (c). A teleseismic record for the same event from a high quality array station located in Norway (distance: 7935 km). Smaller amplitudes and fewer waves lessen the usefulness of such signals for small events.
2. Differences in frequency content can be used to detect explosions in the coda of an earthquake. Panel a shows a Norwegian recording of the signal from an earthquake in Kamchatka together with the signal from an explosion at Semipalatinsk.¹³ The explosion's signal at about $t=100$ s is not readily identified on this record (pass band 1.2-3.2 Hz). Panel (b) shows the same signal processed with a filter that emphasizes the frequencies from 3.2-5.2 Hz. The signal from the explosion at about $t=100$ s is readily discernible.
3. Magnitude-yield relationships from Nevada Test Site explosions and estimated detection thresholds for in-country networks deployed in the Soviet Union (90 per cent confidence of detecting four or more waves) are shown for representative media and networks, respectively. The dashed lines indicate that although explosions less than a kiloton have been detonated in all three environments, the data on the precise magnitude-yield relationships are lacking or subject to significant uncertainty. Note that in areas that are older and more

stable than the Nevada Test Site, the magnitudes of the same explosion could be several tenths of a unit higher.

4. The estimated detection capability of an in-country network varies as a function of the number and type of stations deployed. The calculations shown require a 90 per cent probability of detecting four or more waves. The performance characteristics are based upon properties similar to those described by international networks.⁸ Significantly improved performance characteristics may be possible using improved operational techniques and the properties of carefully selected sites. Uncertainties of several tenths of a magnitude unit are possible because the signal and noise properties in the Soviet Union are unknown. The small box at the left shows the upper range of the estimate for a 1-kt explosion decoupled in a cavity. The dashed line shows the values that might be observed in an older, more stable region. Note that approximately 30 high-performance stations (arrays or possibly high-frequency stations) appear to be required to detect 1 kt with high confidence.
5. The value of different networks depend on the evasion threat. The base case corresponds to 30 high-performance in-country stations or 10 simple stations or external stations operating in an environment where decoupling is feasible. If we assume that decoupling is not feasible, the NTM system is the most attractive because it can detect all the militarily significant tests at no extra cost. Many assumptions are made in these estimates. Their impact can be examined using the decision analysis framework.

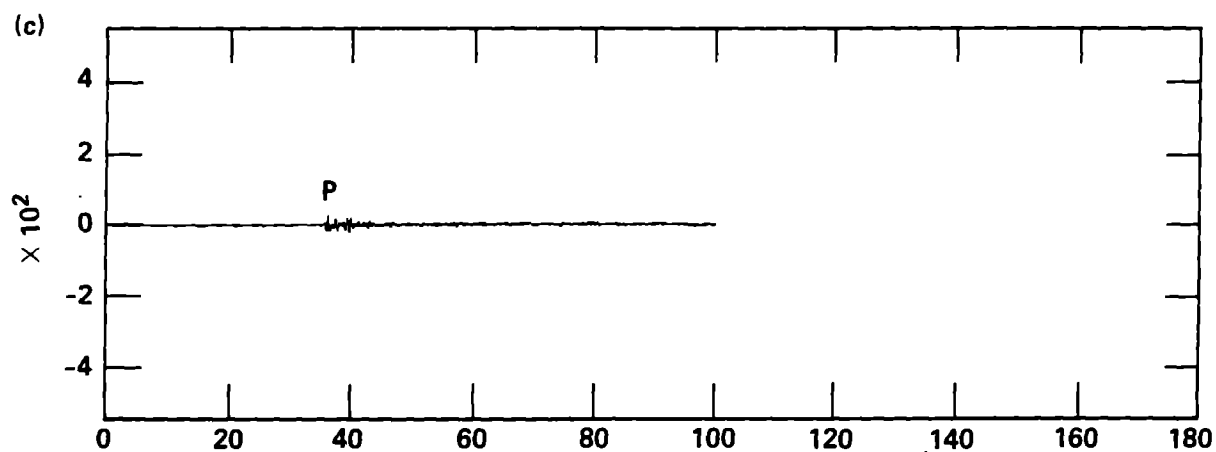
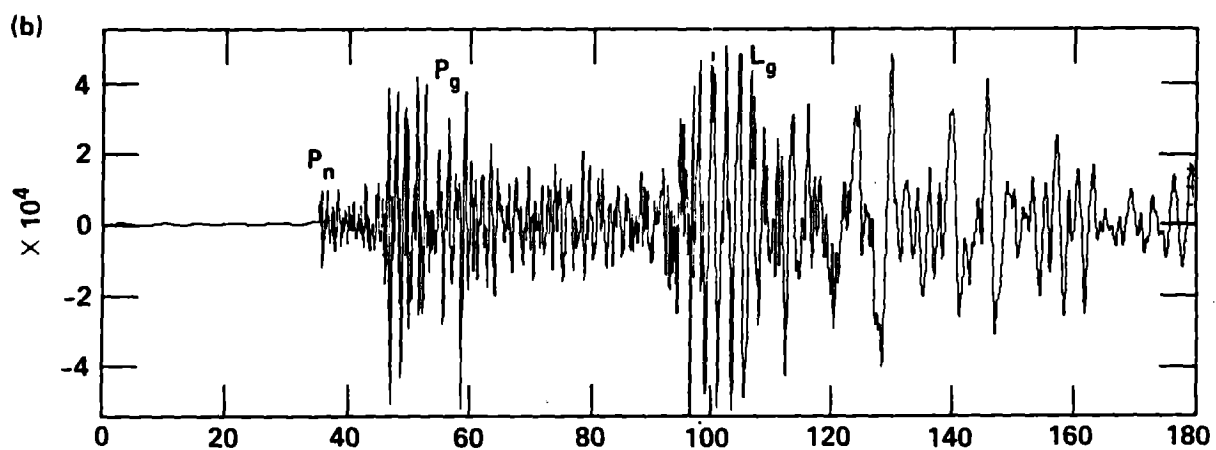
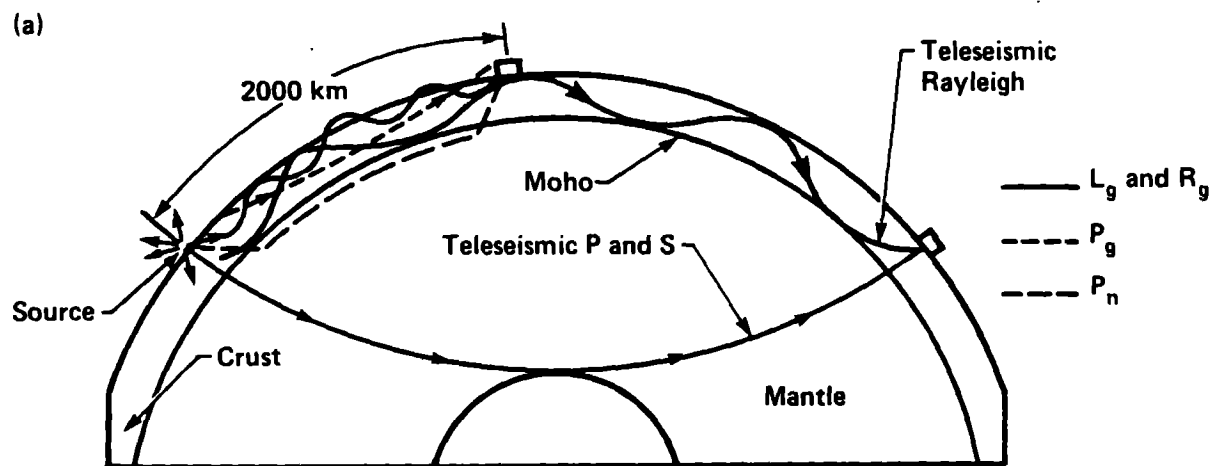


FIG. 1

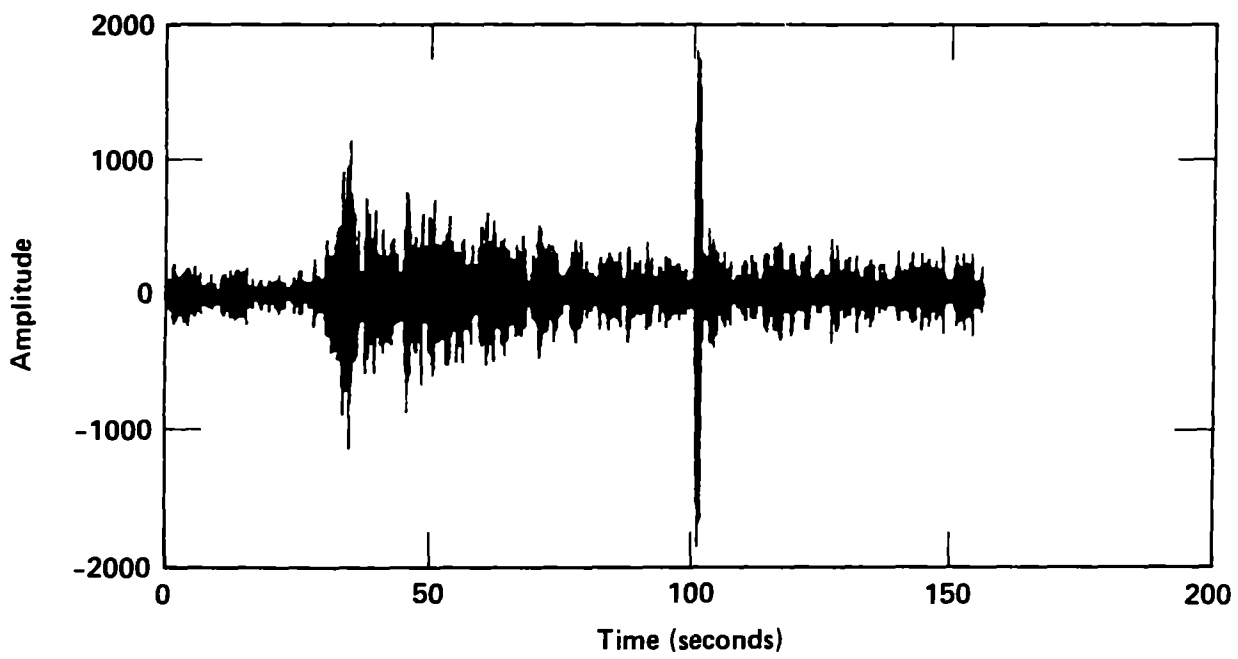
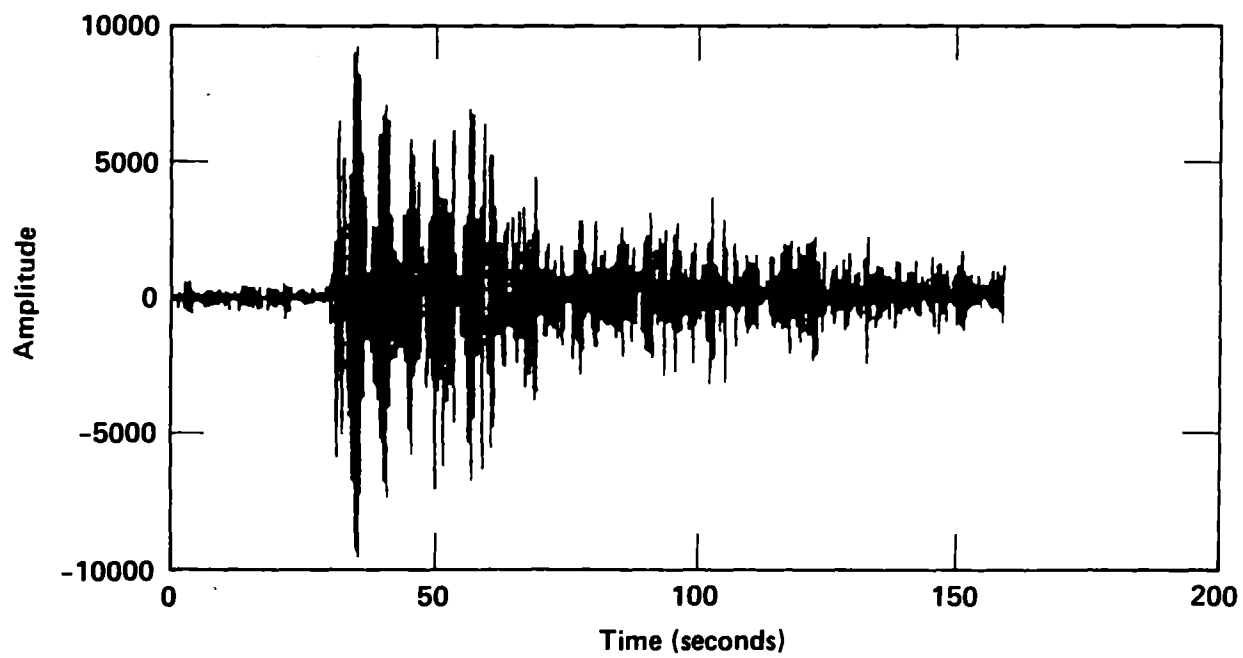


FIG. 2

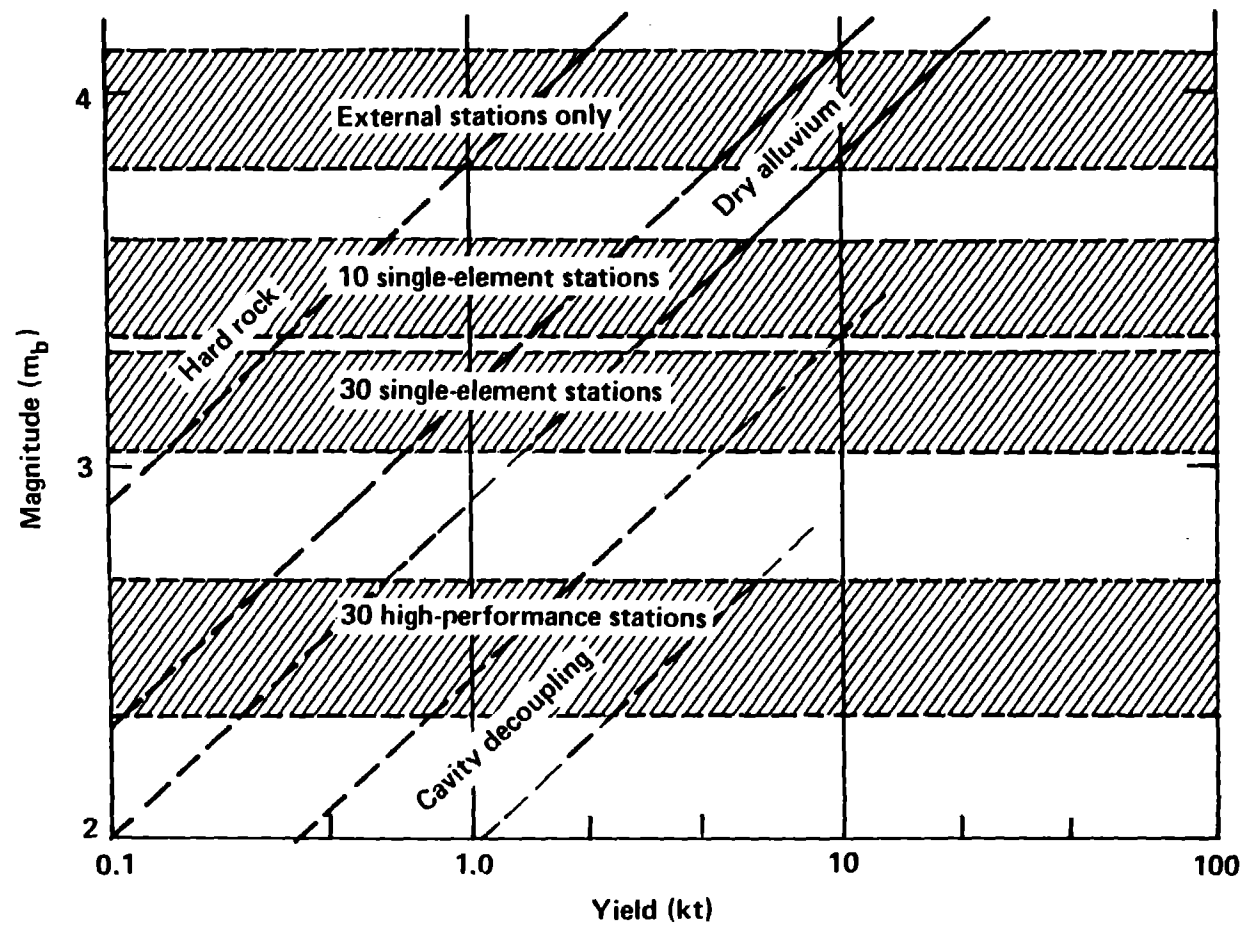


Fig. 3

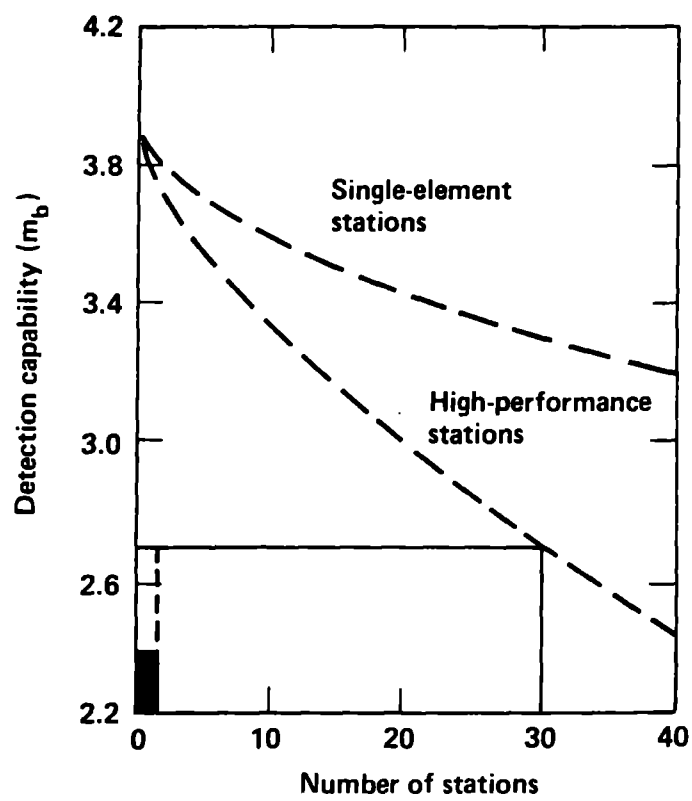


FIG. 4

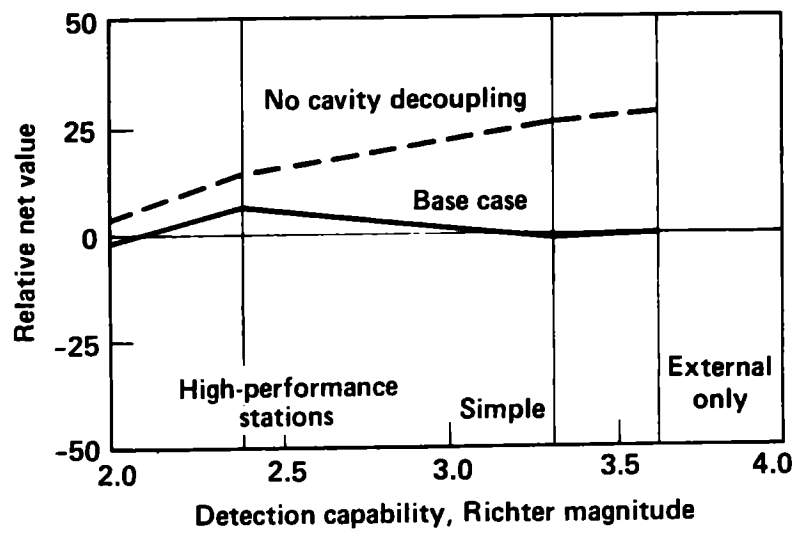


FIG. 5

